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FRACTAL ROUGHNESS CHARACTERIZATION OF SUPER-GROUND Mn-Zn FERRITE SINGLE CRYSTALS

J. YU[*,†], Y. NAMBA[*] and M. SHIOKAWA[*]
[*]Department of Mechanical Engineering, Chubu University,
1200 Matsumotocho, Kasugai, Aichi 487, Japan
[†]State Key Laboratory of Applied Optics,
Changchun Institute of Optics and Fine Mechanics,
Chinese Academy of Sciences, Changchun 130022, P. R. China

Abstract

The surface of superground Mn-Zn ferrite single crystal may be identified as a self-affine fractal in the stochastic sense. The rms roughness increased as a power of the scale from 10^2 nm to 10^6 nm with the roughness exponent $\alpha = 0.17 \pm 0.04$, and 0.11 ± 0.06, for grinding feed rate of 15 and 10 μm/rev, respectively. The scaling behavior coincided with the theory prediction well used for growing self-affine surfaces in the interested region for magnetic heads performance. The rms roughnesses increased with increase in the feed rate, implying that the feed rate is a crucial grinding parameter affecting the supersmooth surface roughness in the machining process.

1. INTRODUCTION

Manganese-zinc (Mn-Zn) ferrite single crystals have been widely used as a core material in magnetic heads for Video Cassette Recorders because of a high permeability in the frequency range of the video signals and a high wear resistance.[1,2] The magnetic heads have been expected to be superground by means of ductile-mode grinding[3,4] in order to meet the required dimensional tolerance. With the development of the magnetic heads machining technology, surface precise evaluation on the scales from nanometer to hundreds of micrometers, is becoming increasingly important since the influence of surface roughnesses may be crucial to performance.

In recent years the descriptions of scaling behaviour have become of crucial importance for many physical problems. A large number of natural surfaces are found to be self-affine, introduced by Mandelbort,[5] such as those encountered in surface growth models,[6] in landscape and erosion surfaces,[7] or in fracture surfaces.[8] The self-affine systems are invariant only under anisotropic magnifications, i.e., the roughness scales anisotropically in the vertical and transverse directions.[5,9–10] Therefore, a scaling analysis is important for the evaluation of surface roughness not only for grown surface[11] but also for super-machining surface, including X-ray optics[12] and the magnetic heads.

In this paper the self-affine roughness characterization of super-ground Mn-Zn ferrite single crystals is investigated with a scanning tunneling microscope and a optical interferometer, and the effect of feed rate f on the roughness is also discussed.

2. EXPERIMENTAL DESCRIPTIONS

Mn-Zn ferrite single crystals of (001) face were cut into small dimension of 9.5 mm × 9.5 mm × 1 mm, a diamond saw wheel being used to grind single crystals, and lapped to be parallel with loose diamond powder. A ultra-precision surface grinder[4] having a glass-ceramic spindle of extremely low thermal expansion was used in this experiment. The machine has the vertical main spindle for a grinding wheel and a low-speed rotary table of 0.01 ∼ 30 rpm. The depth of cut can be controlled at a unit of 0.1 μm.

Mn-Zn ferrite samples have been ground under the ductile-mode conditions,[13] with the wheel speed $V_s = 1200$ m/min, depth of cut $a = 1$ μm (with a SD5000-75-B diamond wheel), and the feed rate $f = 10$, 15 μm/rev, respectively. The grinding direction was ⟨001⟩ on the (001) face.

The surface morphology of the Mn-Zn ferrite samples was studied in a commercial three-dimensional noncontact surface profiler TOPO-3D of WYKO Corp. and a Seiko SAM3500 scanning tunneling microscope (STM). The STM was designed for positioning big samples accurately under a Nomarski interference microscope and for observing details on an exact location by a sharp platinum probe. In order to investigate the scaling behavior: (1) STM measurements were carried out on various areas, i.e., 100 nm × 100 nm, 500 nm × 500 nm, 1 μm × 1 μm, 5 μm × 5 μm, 10 μm × 10 μm; (2) TOPO-3D measurements were carried out on the areas of 235 μm × 232 μm and 968 μm × 956 μm. STM measurements were performed using 0.1 bias voltage with the tip positive at 0.5 nA constant current. In each measurement, data were acquired and stored as digitized images with 256 × 256 pixels. The measuring direction is perpendicular to the grinding direction or marks.

3. RESULTS AND DISCUSSIONS

STM images of Mn-Zn ferrite single crystals with 15 μm/rev feed rate on the areas of 10 μm × 10 μm, 5 μm × 5 μm and 0.5 μm × 0.5 μm are shown in Figs. 1, 2 and 3, respectively. In these figures: (a) is a color gray scale topography of the surface; (b) is a vertical cross section profile of the surface; (c) is a transverse cross section profile of the surface; (d) is a combination of Abbott curve profile and height distribution profile; (e) is a surface top view image. The root-mean-square (rms) roughness values are shown on the bottom right-hand corner of these figures. The self-affine fractal roughness characterization involves the rms roughness, often called the surface width.[11] From the height deviations $z(x, y)$ of the actual surface from its perfect shape, one obtains the three-dimensional rms roughness σ in a square section of size $L \times L$, i.e.,

$$\sigma(L) = \sqrt{\frac{1}{S}\int\int_s Z^2(x, y)dxdy} \tag{1}$$

where S is the area of the scans, $S = L \times L$. As shown in Fig. 1, 2 and 3, with the decrease of scan length from 10 μm to 0.5 μm, i.e., shrinking along the transverse axis by a certain factor, the structures are invariant even under the anisotropic magnifications in a stochastic sense [see Fig. 1(c), Fig. 2(c) and Fig. 3(c)]. In other words, if we cut a small piece out of the original 10 μm $\times$ 10 μm picture, and rescale the transverse axis and vertical axis by a different factor, for example, from 5 μm $\times$ 5 μm or 0.5 μm $\times$ 0.5 μm picture, we will obtain the original picture in the stochastic view. This suggest that the surface of the superground Mn-Zn ferrite single crystals may be identified as a self-affine fractal.

Figure 4 shows the plot of $\sigma(L)$ vs. scanning length L for $f = 15$ μm/rev of a Mn-Zn ferrite sample. On the scales of 10^2 nm $\leqq L \leqq 10^6$ nm, the rms is dependent on the scale as a power law of $\sigma(L) \propto L^{\alpha}$, where the scaling exponent $\alpha = 0.17 \pm 0.04 < 1$. This implies an anisotropic scaling of the surface roughness, and therefore, the surface is identified as self-affine in this scanning region. The scaling behavior shown in Fig. 4 coincides with the theory prediction well used for growing self-affine surfaces,[11,14] i.e., the interface width

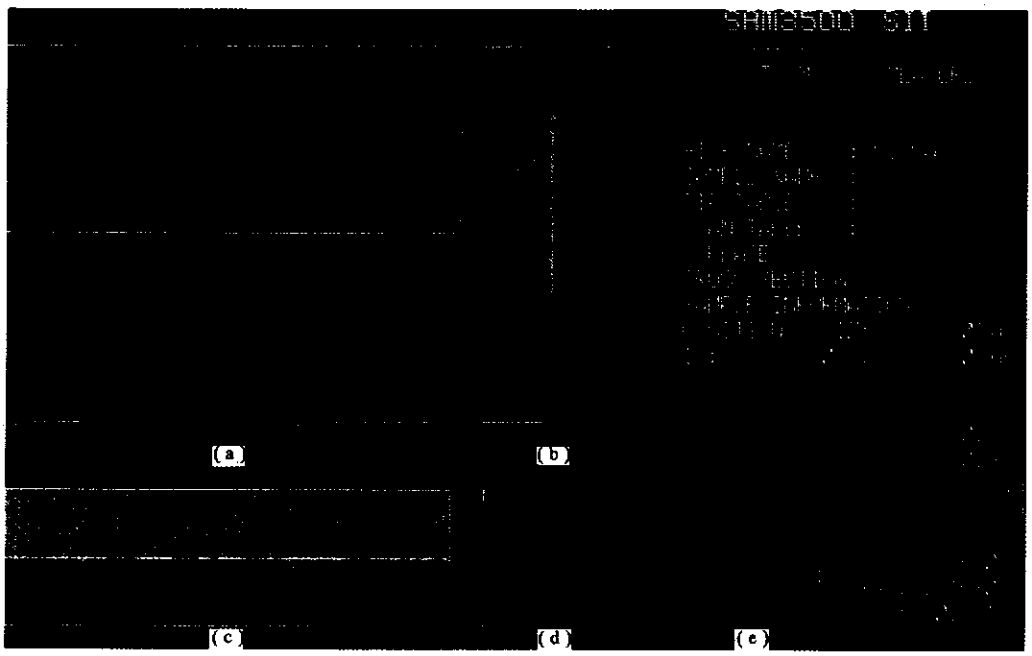

Fig. 1 STM image of Mn-Zn ferrite single crystal with 15 μm/rev feed rate on the area of 10 μm $\times$ 10 μm. **(a)**, **(b)**, **(c)**, **(d)** and **(e)** were explained in the text.

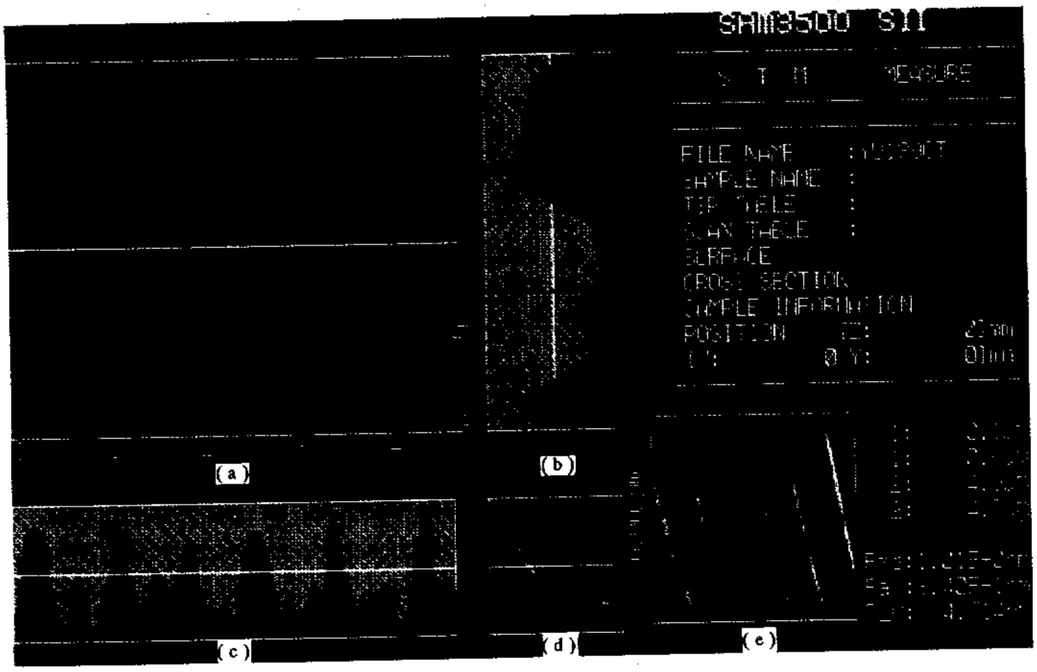

Fig. 2 STM image of Mn-Zn ferrite single crystal with 15 μm/rev feed rate on the area of 5 $\mu m \times 5\ \mu m$.

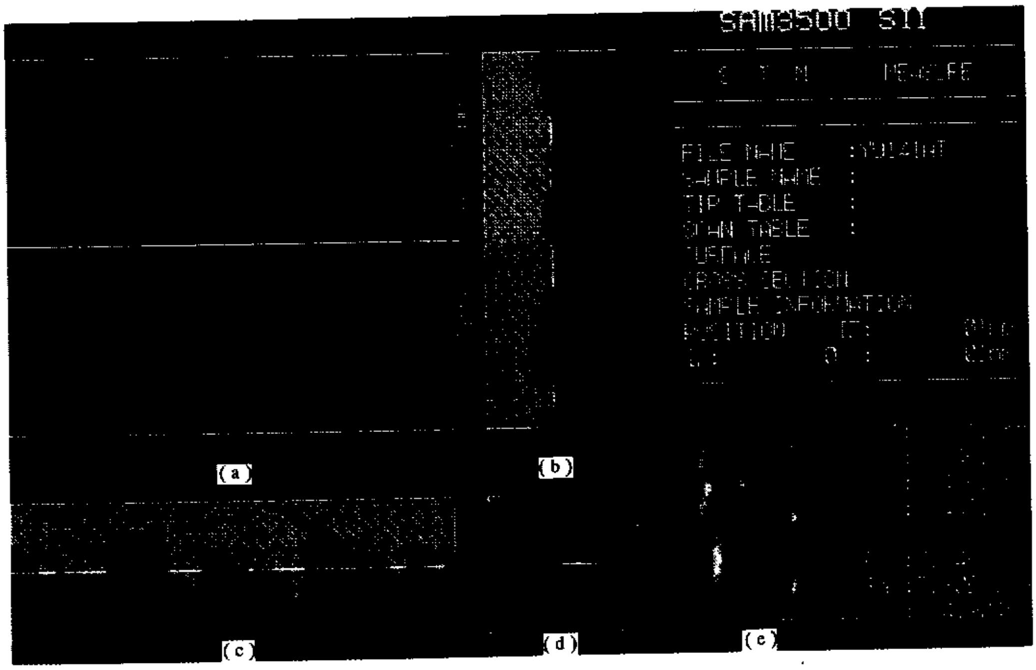

Fig. 3 STM image of Mn-Zn ferrite single crystal with 15 μm/rev feed rate on the area of 0.5 $\mu m \times$ 0.5 μm.

(the rms roughness) $W(L, t)$ for length scale $L \ll L_c$ as

$$W(L, t) \propto L^{\alpha}, \quad \text{for} \quad L \ll L_c \tag{2}$$

where L_c is the correlation length and t is growth time. In Fig. 4 $L_c > 10^6$ nm.

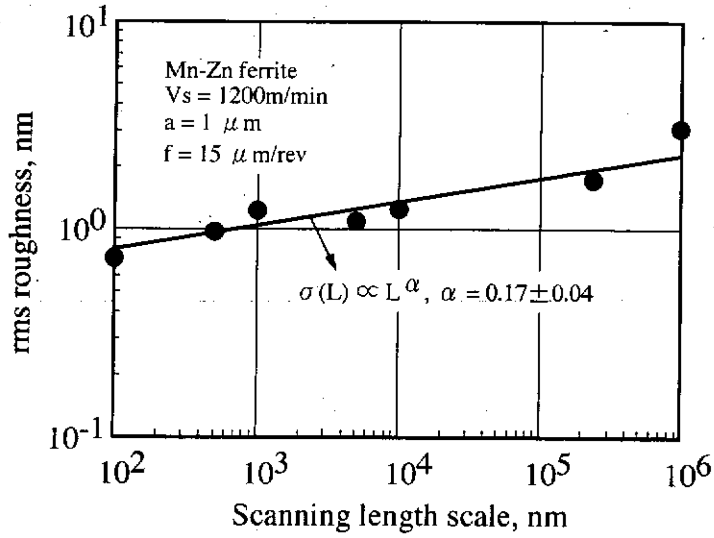

Fig. 4 The rms roughness $\sigma(L)$ vs. scanning length L for Mn-Zn ferrite single crystal of feed rate 15 μm/rev.

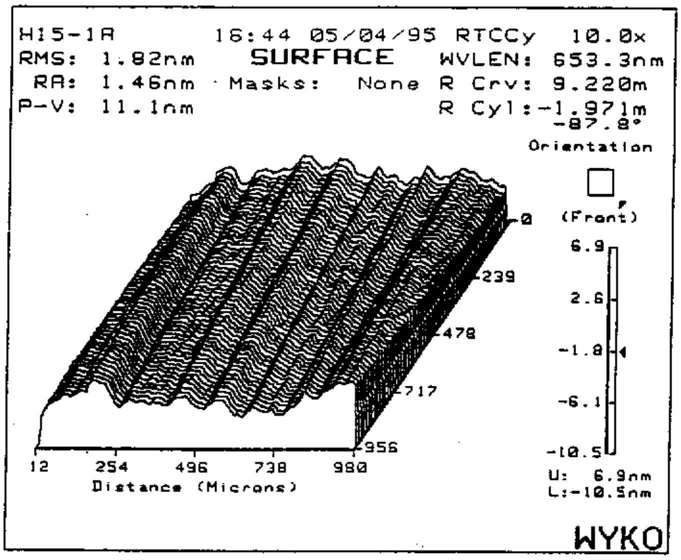

Fig. 5 TOPO-3D topography of the Mn-Zn ferrite single crystal surface of feed rate 10 μm/rev. The area size is 968 μm × 956 μm.

In contrast to the growing films,[14–15] the surface $\sigma(L)$ of the super-ground Mn-Zn ferrite single crystals will "grow" with the increase in the feed rate f. Figures 5 and 6 show the TOPO-3D topography plots of the Mn-Zn ferrite surfaces of 968 μm × 956 μm, 10 and 15 μm/rev, respectively. In Figs. 5 and 6, we observe the maximum height difference between the highest peak and the deepest valley, i.e., P-V values in these figures, become larger from 11.1 nm to 17.4 nm with increasing feed rate, while the rms value is from 1.82 nm to 3.09 nm. This indicates that the feed rate is a crucial grinding parameter affecting the surface roughness for the ultra-precision grinding method.[13] $\sigma(L)$ becomes larger with increase in feed rate.

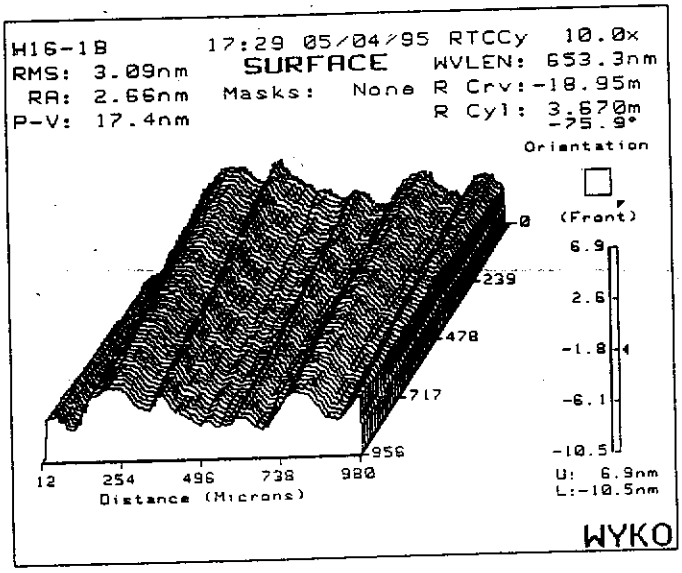

Fig. 6 TOPO-3D topography of the Mn-Zn ferrite single crystal surface of feed rate 15 μm/rev. The area size is 968 μm × 956 μm.

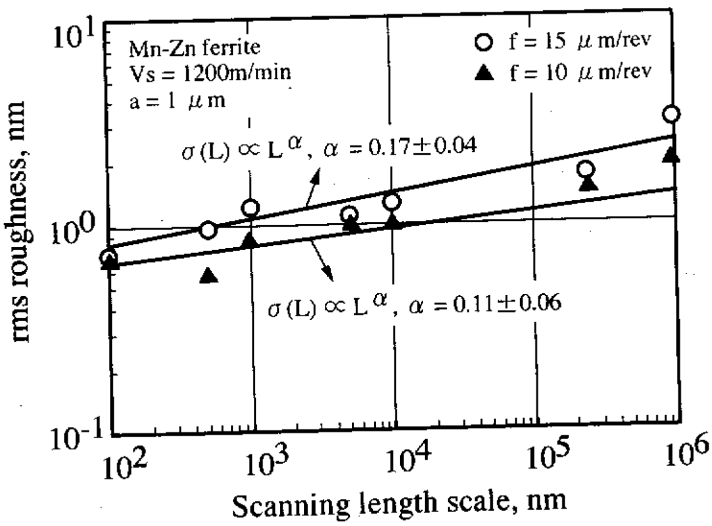

Fig. 7 The rms roughness $\sigma(L)$ vs. scanning length L for Mn-Zn single crystal surface of 10 μm/rev and 15 μm/rev feed rate under the same grinding conditions.

Figure 7 shows the plot of $\sigma(L)$ vs. L for Mn-Zn samples of 10 μm/rev and 15 μm/rev under the same grinding conditions. For each feed rate, $\sigma(L)$ increases as a power of L, and the roughness exponent α of 10 μm/rev sample is 0.11 ± 0.06. Furthermore, Fig. 7 clearly shows on the interested scales, from a hundred nanometers to hundreds of micrometers, the rms roughness increasing with increase in the feed rate.

4. SUMMARY

In this study, the fractal roughness characterization of superground Mn-Zn ferrite single crystals was investigated. The experimental results show that the surface of the superground

Mn-Zn samples may be identified as a self-affine fractal in the stochastic sense. The rms roughness increased as a power of the scale from 10^2 nm to 10^6 nm with the roughness exponent $\alpha = 0.17 \pm 0.04$, and 0.11 ± 0.06, for feed rate of 15 and 10 μm/rev, respectively. The scaling behavior coincided with the theory prediction well used for growing self-affine surfaces in the interested region for magnetic heads performance. Such scaling behavior should be taken into account in the theoretical calculation of the surface performance, and also in metrology of roughness parameters. On the interested region, from 10^2 nm to 10^6 nm, the rms roughnesses increased with increase in the feed rate, implying that the feed rate is a crucial grinding parameter affecting the surface roughness in the machining process.

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